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Asian Resonance

Recent Developments in Magnetic Refrigeration and its Applications

Magnetic heating, refrigeration and Energy conversion have caused awareness of being promising future environmentally benign with much potential to enter some existing market. An increased research activity is observed. In this article new systems ideas are presented, which may have the potential to overcome existing barriers. The article is proposal to to research community in the field of magnetocaloric technologies for future R&D activities. The experimental prototype describe in this work is a hybrid refrigerator that combines the active magnetic refrigeration effect with stirling gas regenerative effect. In this prototype, gadolinium sheets are packed in the regenerator matrix for both stirling and active magnetic regenerative refrigeration. Experimental tests are carried out to measure the cooling performance of this hybrid prototype. A high performance magnetic refrigeration device is considered as a potential for in vehicle air conditioner in electric vehicles. The high power consumption of a conventional air conditioner in an electric vehicle has considerable impact on crusing distance for this purpose the demand on cooling power density, temperature difference between hot and cold side, transient properties and COP, will be high. In this paper the potential to reach this demands are explored for two technologies, firstly a conventional AMR device and secondly a novel magnetocaloric device based on control of the axial thermal conductivity.

Keywords: Magnetic refrigeration, Active magnetic regenerative effect, Magneto-caloric effect, Research, Developments, Hybrid refrigerator, stirling gas refrigerator

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Introduction

Magnetic refrigeration was first studied 130 year ago, when Warburg first discovered the magneto-caloric effect (MCE) (Warburg, 1881). Magnetic refrigeration based on MCE is become increasingly attractive because of its environmentally friendly features. Because solid magneto-caloric materials produced no ozone depleting or green house effects.X.N.He,M.Q.Gong, H.Zhang, W.Dai,J.F. Wu(2013) Magnetocaloric devices are magnetic heat pumps, magnetic refrigerator or magnetic energy conversion machines. Up-to-present more than forty heat pumps and refrigerator prototypes have been built and tested all over the world (see Yu et al, submitted for publication). Most prototype apply a periodic magnetization /demagnetization process which is realize by a motion of solid magnetocaloric material through a static magnetic field or by motion of magnet's assembly over a static magnetocaloric material bed.(Andrej Kitanovski,Peter W. Egolf,2010). Usually magnetization leads to heating up process and demagnetization to opposite cooling of a magnetic material. If a fluid cools magnetized hot material and demagnetized cold material absorbed heat from a fluid transporting heat from heat source, the principal of magnetic heat pump, respectively magnetic refrigerating machine is realized. In this cases, the magnetic material has to be forced into magnetic field machine has a work input. In reverse process of magnetic energy conversion, a heat input leads to driving a magnetic material, which can be transformed to create mechanical or electrical energy these principals are described in details Kitnovaski Egolf (2009)and reference given therein for magnetic heating and cooling and Egolf et al. (2009) for magnetic energy conversion.

However, the active magnetic refrigeration effect at room temperature is steel quite weak when compared with the widely used vapour compression refrigeration effect, regardless of temperature span or cooing capacity. Therefore, some researcher have tried to combine the gas regenerative cooling effect. However, most efforts have been made in cryogenic temperature zone. An experimental prototype of hybrid cryocooler was constructed and tested by nellis and smith at MIT (1996).

This distinct experimental prototype combined the Gifford-McMahon (GM) gas refrigeration effect. The prototype reached a no load temperature of 4.5 K and could provide 0.36 W at 5.6 K. YaYama et al. (2000) proposed anew cryogenic refrigerator that hybridised the Brayton magnetic cooling cycle and GM gas cooling cycle. They evaluated the refrigeration power of the refrigerator at approximately 4.2 K by numerical simulation

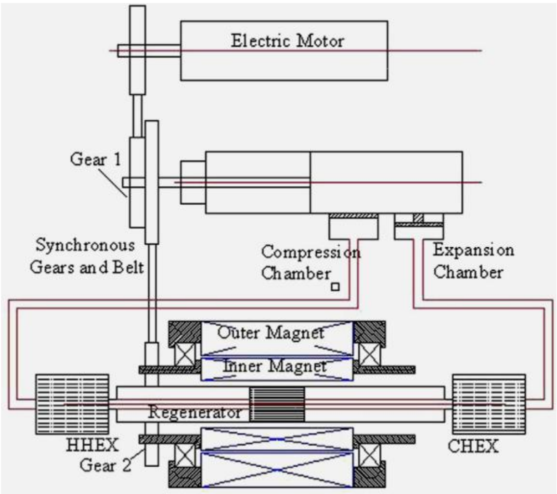

Fig. 1 – schematic diagram of the hybrid refrigerator: Gear 1 determine the start value of compression and gear 2 determine start of magnetic field.

Numerical solution have been performed to explore the feasibility of in-vehicle magnetic refrigeration. An ambitious goal of comparatively high cooling power density and large temperature difference between the hot cold sides has been set. The goal has been deemed necessary to place magnetic refrigeration as a viable option for electrical vehicles. In order to reach the goal an open-minded parameter search has explored the limitation of multiple systems, both conceptual and well-established. One set of simulations has been made stretching the parameter space of a conventional AMR device (Bahl et al.,2008) and another has been made considering a novel solid state approach (Tasaki et al., 2012). Extreme material properties have been invoked to fix performance boundaries and aid to find the most promising development paths.

The ambitious has been set to obtained significant cooling power at a temperature span of 60°C. The high temperature will ensure sufficient temperature difference between ambient temperature and heat exchangers to give cooling in extremely hot environments and still run the heat exchanger efficiently. Experimental results with conventional compression cooling will typically give~1-2kW cooling in this condition with COP of ~1-2 depending on operation conditions (Joudi et al., 2013) the figures demonstrate the nee d for more efficient units to be used in electrical vehicles.

Magneto-Caloric Effect

When the magneto-caloric material is not exposed to magnetic field, the magnetic moments in the material are disordered or randomly oriented. However, when the magnetic field is applied, the magnetic moment becomes oriented in the direction of the applied magnetic field. From the magnetic point of view the system has reduced magnetic entropy (Sm), means that in an adiabatic system the temperature of material must increase. A reverse when the process is observed magneto-caloric material from the magnetic field is removed, and the magnetic moments reverse to random orientations. This cause an increase in the magnetic entropy and corresponding decrease in the temperature. As a result, the system cools down.

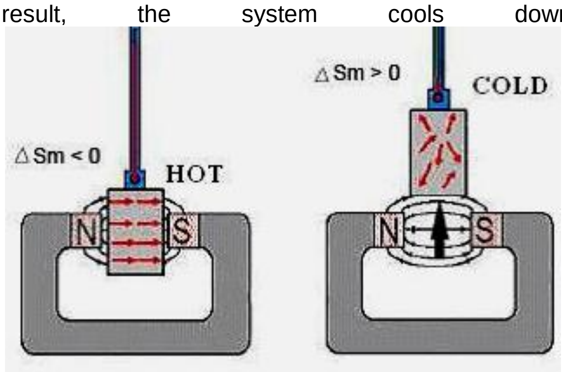

Fig. 2 –scheme of magneto-caloric effect.

The magneto-caloric effect can be described as a change of magnetic entropy or adiabatic temperature of the magneto-caloric material subjected to magnetic field.

Operation In Magnetic Refrigerator

In general the magnetic refrigerator is composed of magneto-caloric material in teh form of porous structure called the active magnetic regenerator (AMR). AMR has a role of refrigerant (it contains the magneto-caloric material) as well as role of regenerator. Heat generation between the particular phases of the cooling process assures an increase of the temperature range, which is crucial to the magnetic cooling at room temperature. So, AMR configuration overcomes the limitation imposed by relatively small magneto-caloric effect of the, so far known magneto-caloric materials.

In addition, the basic elements of the magnetic refrigerator are the following: a structure to generate magnetic field (electromagnetic device or permanent magnet), two external heat exchangers and the fluid which transfer heat from magneto-caloric in the AMR through two external heat exchanger from the cooling space and to the surrounding.

Experimental Setup

Principles Of Hybrid Refrigerator

The stirling gas regenerative refrigerator cycle consist of compression and expansion cylinders, each fitted with a piston. The two cylinders are connected via a regenerator, which has a temperature gradient. The typical stirling gas regenerative refrigeration cycle consist four thermodynamic process.

Compression process; the gas is compressed by compressor piston, expelling compression heat to the environment.

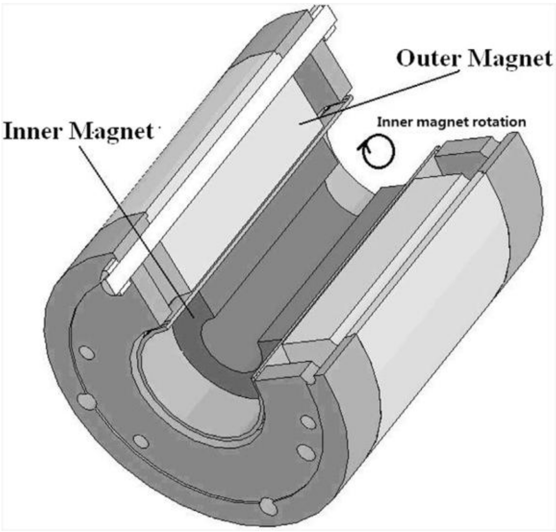

Fig. – 3 Concentric Halbach cylinder permanent magnet.

Fig. – 4 Photograph of inner Halbach array magnet.

Hot-to-cold process; the gas is displaced through the regenerator via a constant volume process by the simultaneous moments of both pistons. In this step, the gas exchange heat with regenerator material.

Expansion process; the gas is allowed to expand against the expansion piston.

Cold-to-hot process; the gas is displaced back through the regenerator to the compression space by a simultaneous moment of pistons. In this step, the heat that was transferred to regenerator from the hot-to-cold process is transferred back from the regenerator to gas.

The configuration of a typical active magnetic regenerative refrigerator can be described as follows: An active magnetic regenerator filled with magneto-caloric materials, a displacer which drives the heat transfer fluid, a cold heat exchanger which release heat to fluid and hot heat exchanger absorbing heat from fluid.

Fig. – 5 Photograph of outer Halbach array magnet.

Prototype Construction.

Based on the principle described above, a hybrid magnetic refrigeration prototype combined with stirling gas regenerative refrigeration was designed and manufactured. It consist of five major parts listed below:

1. A concentric Halbach cylinder permanent magnets (Bjork et al., 2010) consist of inner and outer Halbach cylinders coupled together with bearings to provide an alternating magnetic field from 0 to 1.5 T. The Halbach array is a hollow cylindrical permanent magnet array which is widely used in magnetic refrigeration system to generate magnetic field. In our experimental prototype, the concentric Halbach cylinder is consist of inner and outer Halbach array, the inner and outer Halbach array are both composed of 16 segments of permanent magnets.

Parameters	**Value**
Heat transfer gas	**Helium**
Magneto-caloric material	**Gadolinium sheet**
Gd sheet height	**8mm**
Gd sheet thickness	**1mm**
Porosity	**0.62**
Charged helium pressure	**1Mpa**
Operating frequency	**1.5Hz**
Gas displacer stroke	**40mm**
Regenerator diameter	**29mm**
Regenerator length	**80mm**
Piston diameter	**54mm**
Matrix quality	**198gm**

Experimental Parameters

1. A stainless steel tube packed with Gd sheets acts as the hybrid regenerator that supports both the stirling gas refrigeration effect and the active magnetic regenerative refrigeration effect.
2. There is one cold heat exchanger for cooling capacity output and one hot heat exchanger for heat rejection;
3. There are two piston and cylinder for stirling gas compression and expansion, which also act acting as the heat transfer fluid displacer for AMRR;

4. An electric motor with a synchronous system is used to drive two permanent pistons and the concentric Halbach cylinder permanent magnet, in which there is control mechanism for adjusting the phase angle and operating frequency.

Experimental Results.

The extensive tests on hybrid refrigerator has been carried out. All tests were performed at acharged helium pressure of 1.0 MPa and operating frequency of 1.5 Hz. The focus of this work was studing the influence of the phase angle and the cooling performance. The cooling curves at different heat loads of the hybrid refrigerator are shown in fig.5 where cooling curves with and without MCE are illustrated.

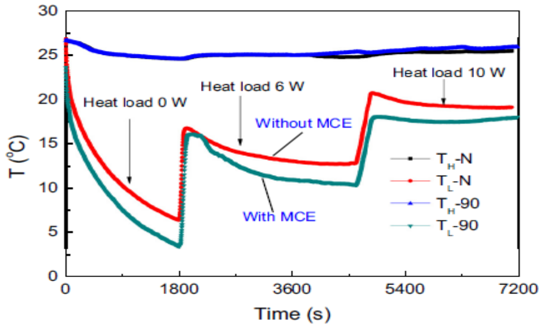

Fig. – 6 cooling down curves under different heat loads

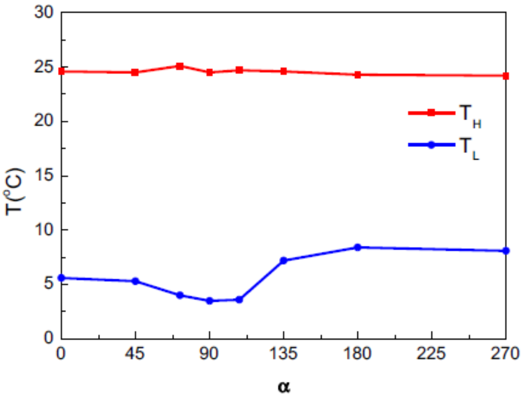

Fig.- 7 cold end temperature Vs. Phase angle.

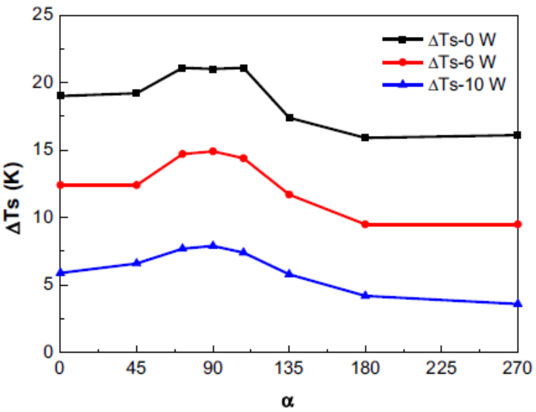

Fig. – 8 Temperature span Vs. Phase angle.

Conclusion.

A hybrid refrigerator combining the stirling gas refrigeration effect with the active gas magnetic refrigeration effect at room temperature was designed, fabricated and tested. In this machine the magnetic field varying from 0 to 1.5 T was provided by the Halbach type permanent rotary permanent magnet and helium gas was used as the heat transfer fluid. Using 198 g Gd sheets, experiments at various phase angles, a gas pressure of 1MPa and operating frequency of 1.5 Hz were conducted. A n0-heat-load temperature of 3.5°C at the cold heat exchanger was achieved, which is lower than that of 6.5°C for pure stiling gas refrigeration under same operating condition but without MCE, which was eliminated by stopping the rotating magnet. A reasonable phase angle of 90°C was determined to obtained the cooling performance of the hybrid cycle. Cooling power of 6 and 10 W were achieved over a temperature span of 14.9 and 7.9 K, respectively. Meanwhile, at the same cooling power, the temperature span increased by up to24% in the hybrid machine relative to the spans exhibited under pure stirling gas refrigeration.

Models For In Vehicle Magnetic Refrigeration.

The work presented in this paper model two different design for magnetic cooling device. Firstly model V, a conventional AMR design using parallel plate regenerator and aqueous solution as heat transfer fluid. Secondly model D, a novel design proposed by Kitanovski and Egolf (2010) and further development by Nissan (tasaki et al., 2012) utilizing the conceptual properties of thermal switches to avoid the use of heat transfer fluid

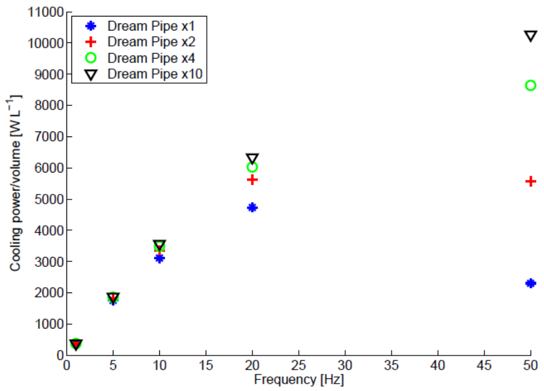

Fig. – 9 **Cooling Power Vs. Frequency (Hz). For Dream Pipes.**

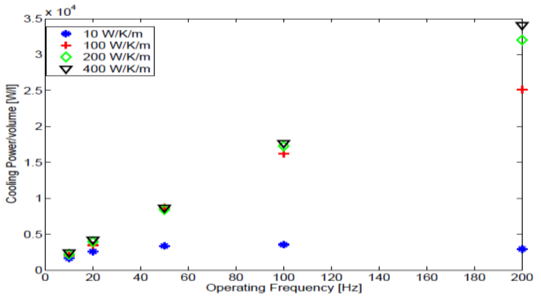

Fig. – 10 **Cooling Power Vs. Operating Frequency (Hz).**

For both models a graded magneto-caloric material (MCM) has been used. Since the study intends to explore and compare the nature of two regenerator configuration the material properties have been taken from the MFT model (Morrish, 1965, petersenet al., 2008). The high temperature difference makes a single material regenerator unfeasible (Nielsen et al., 2010). Instead of just using an arbitrary higher number of materials a perfectly graded MCM has been implemented. Similar approach is used by Bjork et al., (2011) although with a ΔTad constant in temperature. In this study each numerical node in this material was assign a curie temperature corresponding to its temperature. The temperature of node was found from its position and a linear thermal profile between the heat exchange. The thermal of the hot and the cold heat exchanger are 308K and 248K respectively.

Model V.

This model has MCM in the form of parallel plates and water is used as a heat transfer fluid. The operation of AMR cycle consist of 4 parts lasting a total time,τ: 1. The MCM is magnetized, 2. Hot blow, the fluid is pushed from the cold to hot reservoir, 3. The MCM is demagnetized, 4. Cold blow, the fluid is pushed from hot to cold reservoir. Magnetization and demagnetization occure linearly and lasts and equal time 1. The two blows also last an equal time 2. The length of fluid is pushed is characterized by its ratio the length of the MCM.

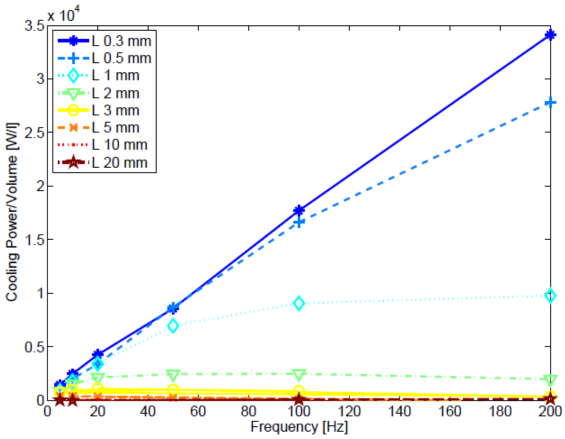

Fig. – 11 **Cooling Power Vs. Frequency (Hz) For Different Lengths.**

The study has the aim of exploring the boundaries of performance. It is recognized that thermal contact to the heat transfer fluid plays an important role performance of an AMR device (Dragutinovic and Baclic, 1998). In the pursuit of increasing increasing the thermal contact the influence of the plate surface has attracted the attention of research. Several methods have been reported that could increase the heat transfer of the fluid to the walls of a pipe of travelling fluid. In this study such a “Dream pipe” effect has been generalized as an increase of nusselt number is multiplied with dream pipe factor.

Model D

The second model is further described by tasaki et al. (2012).This model relies on a concept of thermal switches (TS) to control the direction of heat transfer. The cycle for this model consist of alternating magnetization of every other MCM segment. The magnetic field is applied for half a cycle with a linear ramping time lasting 5% of the cycle time corresponding to 1/10 =0.1. For a magnetized segment the Ts towards the hot side is open while the TS towards the cold side is closed. The TS change discretely between being conducting with the TS conductivity given below and having a conductivity of 0 W (K m)^-1. For a demagnetized segment the open and closed sides are reversed.

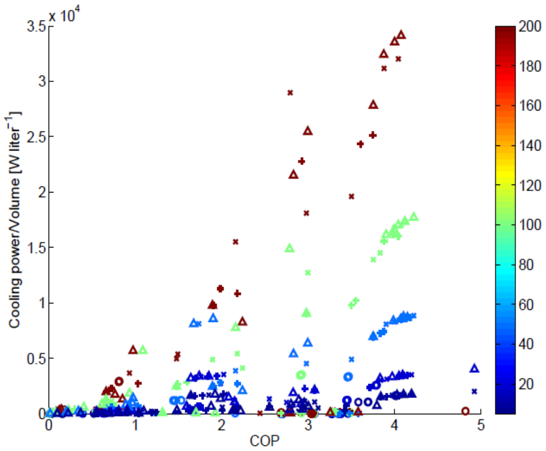

Fig. – 12 **Cooling Power Vs. COP**

Results

In both models a temperature span of 60 K has been set, as discussed above, and the resulting cooling power is calculated. As expected the high performance goals limit the number of configuration that results in a positive cooling power. In the following only results with a positive cooling power are reported. Since the size of the device is an evaluation in the study the cooing power is reported as a function of the volume of the device. For model V the volume is take as the volume of MCM and the volume of fluid channels of the MCM and the volume of the TS’s. In both cases heat exchangers, magnets and auxiliary components have been left out for clarity of the investigated subject. The of the collective system has previously been performed for an AMR like fluid model (Bjork et al,. 2011).

Thermodynamical Comparison.

The frequency is 20 Hz in both models for the other parameters: Dream pipe factor is 10; relative stroke length is 0.2; relative stroke time is 0.5; and total length is 12 cm for V model. For D model the MCM and thermal switch conductivity is both 400 W (K m)^-1 and segment length is 0.3mm. values are shown for the few regularly spaced nodes that are calculated in the algorithm. The role of heat transfer fluid and the thermal switches is not included in T-S diagram which only shows the value MCM. For each node make a closed circuit during the course of cooling cycle.

	Qx graph [W L^-1]	Qx model [W L^-1]	Work graph [W L^-1]	Work model [W L^-1]	COP graph	COP model
Model D	3365	3345	825	828	4.1	4.0
Model V	2167	5833	915	2917	2.4	2.0

Model D and model V work thermodynamically very differently. While the D model nodes extend across a temperature range corresponding to ΔTad, the V-model node extend more than 15K. This this corresponds to the thermal neighbourhood of the two models. In D model heat is exchange of the two neighbourhood corresponding to 3 of the 24 segments or 12.5% of 60 K temperature range. For V-model the relative stroke length is 0.2 corresponding to 20% of the temperature range. In the effort of tailoring the MCM transition temperature to the operating condition this difference in operation is interesting to node, especially considering the narrow temperature range of the MC effect that some of the most promising material exhibit (Cam Than et al., 2006).

Conclusion

We have presented the result from a numerical study of two very different models for active magnetic refrigeration. Firstly a conventional fluid model utilizing 50µm plates of perfectly graded Gd-like material. This model has enhanced heat transfer between MCM and fluid by means of a “dream pipe” effect. This effect was implemented by a multiplied factor of the nusselt number. Maximum cooling power of this model is 10KW L^-1. Secondly a conceptual model was evaluated. The model uses thermal switches to control the heat flow in the MCM thus dispensing with the heat transfer fluid. In this model the thermal conductivity of the MCM was increased between 10 and 400 J (Kg K)^-1. The maximum cooling power of this model is 34 KW L^-1.

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